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Non-Baryonic Dark Matter – A Theoretical Perspective

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Abstract. I review axions, neutralinos, axinos, gravitinos and super-massive Wimpzillas as dark matter candidates.

INTRODUCTION

Some twenty years after the dark matter (DM) problem was taken seriously by particle theorists, we still don't know the exact nature of the hypothetical non-luminous material of which presumably extended halos around galaxies and their clusters are made [1]. While there may well be more than one type of DM, arguments from large structures make us believe that a large, and presumably dominant, fraction of DM in the Universe is made of some massive particles which at the time of entering matter dominance would be already non-relativistic, or *cold*. From the particle physics point of view, cold DM (CDM) could be made of some particles which would generically be called weakly interacting massive particles (WIMPs).

WIMPs do not necessarily have to interact only via weak interactions *per se*. One expects that they should preferably be electrically and color neutral, and therefore be, as it is often stated, "non-baryonic". Otherwise, they would dissipate their kinetic energy. (Aspects of baryonic DM are discussed in Ref. [2] (MACHOs) and [3] (Q-balls).)

Among WIMPs, there exist several interesting candidates for CDM which are well-motivated by the underlying particle physics. The neutralino of supersymmetry (SUSY) is considered by many a "front-runner" by being perhaps the most "generic" WIMP. The axion is another well-motivated candidate. But by no means should one forget about other possibilities. While some old picks (sneutrinos and neutrinos with mass in the GeV range) are now ruled out, axinos and gravitinos have recently been revamped as possibilities for CDM. A new type of super-heavy

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Wimpzilla has also been proposed. In this talk I will briefly summarize main results and review recent developments in the field of WIMP and WIMP-like DM.

Neutrinos, the only WIMPs that are actually known to exist, are not considered particularly attractive as DM candidates. It has long been believed that their mass is probably very tiny, as suggested by favoured solutions to the solar and atmospheric neutrino problems, which would make them hot, rather than cold DM. This picture has recently been given strong support by first direct evidence from Superkamiokande for neutrinos' mass [4]. While the new data only gives the $\mu - \tau$ neutrino (mass)^2 difference of $2.2 \times 10^{-3}\,\mathrm{eV}^2$, it it very unlikely that there would exist two massive neutrinos with cosmologically relevant mass of 5 to 40 eV and such a tiny mass difference.

Current estimates of the lower bound on the age of the Universe lead to $\Omega h^2 < 0.25$. Recent results from high-redshift supernovae type Ia imply $\Omega_{\mathrm{matter}} \simeq 0.3$. The Hubble parameter is now constrained to 0.65 ± 0.1. Since $\Omega_{\mathrm{baryon}} h^2 \lesssim 0.015$, one obtains $\Omega_{\mathrm{CDM}} h^2 \lesssim 0.15$ or so. Assuming that CDM accounts for most of matter in galactic halos, one obtains a very rough estimate $\Omega_{\mathrm{CDM}} h^2 \gtrsim 0.025$.

AXIONS

Axions are spin-zero particles which are predicted by the Peccei-Quinn (PQ) solution [5] to the strong CP problem. As it is well known, the Lagrangian of QCD allows for a PC-violating term $\frac{\alpha_s}{8\pi}\bar{\theta} G\widetilde{G}$, where G is the gluon field strength. This term would contribute about $5 \times 10^{-16} \bar{\theta}\,\mathrm{e\,cm}$ to the electric dipole moment of the neutron, thus violating the current experimental bound by some ten orders of magnitude. In order to explain the required strong suppression in the value of $\bar{\theta}$, Peccei and Quinn postulated a new global $U(1)$ symmetry which would be spontaneously broken at some scale f_a. The pseudogoldstone boson associated with this scenario is the axion [6]. Because of a QCD chiral anomaly, the axion acquires mass $m_a \approx \Lambda_{QCD}^2/f_a$ where f_a is *a priori* an arbitrary parameter.

Axions are also relevant cosmologically. A variety of astrophysical and cosmological constraints have now narrowed the range of axion mass to $10^{-6}\,\mathrm{eV} \lesssim m_a \lesssim 10^{-3}\,\mathrm{eV}$ (which corresponds to $10^{(9-10)}\,\mathrm{GeV} \lesssim f_a \lesssim 10^{12}\,\mathrm{GeV}$) in a broad range of axion models. Rather remarkably, in this mass range, axion relic abundance is of order one, making them a possible DM candidate. Because they are produced out of thermal equilibrium, axions quickly become non-relativistic and are cold relics.

Axions are currently being searched for in microwave cavities immersed in a strong magnetic field, as reviewed in a separate talk by Sadoulet [7].

NEUTRALINOS

The DM candidate which has attracted perhaps the most attention from both the theoretical and experimental communities is the neutralino. It is a neutral

Majorana particle, the lightest of the mass eigenstates of the fermionic partners of the gauge and Higgs bosons: the bino, wino and the higgsinos. It is massive and, if it is the lightest SUSY particle (LSP), it will be stable due to assumed R-parity. A perfect candidate for a WIMP! There is much literature devoted to the neutralino as DM, including a number of excellent reviews (see, *e.g.*, Ref. [8]). Here I will only summarize the most essential results and comment on recent developments and updates.

Neutralino properties as DM and ensuing implications for SUSY spectra are quite model dependent but certain general conclusions can be drawn. Two benchmark models are normally considered. One is the supersymmetrized Standard Model (MSSM) with a minimum number of GUT assumptions about the form of superpartner soft SUSY-breaking mass terms. Of relevance here is the assumption that the masses of the bino, wino and gluino (the fermionic partner of the gluon) are equal at the GUT scale $M_{\rm GUT} \simeq 2 \times 10^{16}\,{\rm GeV}$. The other, much more predictive, model is the Constrained MSSM (CMSSM), or an effective minimal supergravity model. In the CMSSM one assumes that not only gaugino but also scalar (sfermion and Higgs) soft SUSY-breaking masses unify to $m_{1/2}$ and m_0, respectively, at a GUT scale. Masses of all the superpartners at the Fermi scale are then obtained by running RGE's down from $M_{\rm GUT}$ to m_Z. Higgs masses are determined through the condition of electroweak symmetry breaking (EWSB).

It is now generally accepted that the neutralino as DM candidate should most naturally contain a dominant bino component [9]. The (admittedly rough and subjective although commonly used) argument in the MSSM is that of naturalness: no superpartner masses are expected to significantly exceed 1 TeV. This, because of GUT-related relations among the masses of the gluino, the wino and the bino, $M_1 \simeq 0.5 M_2$ and $M_2 \simeq 0.3 m_{\widetilde{g}}$, implies $m_\chi \lesssim 150\,{\rm GeV}$. Of course this bound is only indicative but it gives us some idea for the expected range of m_χ. Another implication is that, because of the structure of the neutralino mass matrix, higgsino-like neutralinos are also strongly disfavored (the region $|\mu| \ll M_2$ where μ is the Higgs/higgsino mass parameter) [9].

Remarkably, in the CMSSM, the bino-like neutralino typically automatically *comes out* to be the LSP in a very large part of the SUSY parameter space [10,11]. This happens mostly as a result of imposing EWSB which typically produces $|\mu| \gg M_2$. Because of this property, and the fact that, roughly, $\Omega_\chi h^2 \sim m_0^4/m_\chi^2$, one is often able to put a *cosmological* ($\Omega_\chi h^2 < 0.25$) upper bound on SUSY mass parameters. Remarkably, the bound in the ball-park of 1 TeV, as generally expected for low-energy supersymmetry! To me this remarkable property is a powerful illustration of the unity of particle physics and cosmology. While this attractive picture holds over large ranges of parameters, it has some loop-holes. For large $\tan\beta$, the bound disappears in a broad range around $m_A/2$ (half of the mass of the pseudoscalar Higgs) where the annihilation cross-section becomes large. Another effect which has recently been pointed out is the neutralino's co-annihilation with the next lightest $\widetilde{\tau}_R$ in the region of $m_{1/2} \gg m_0$ [12].

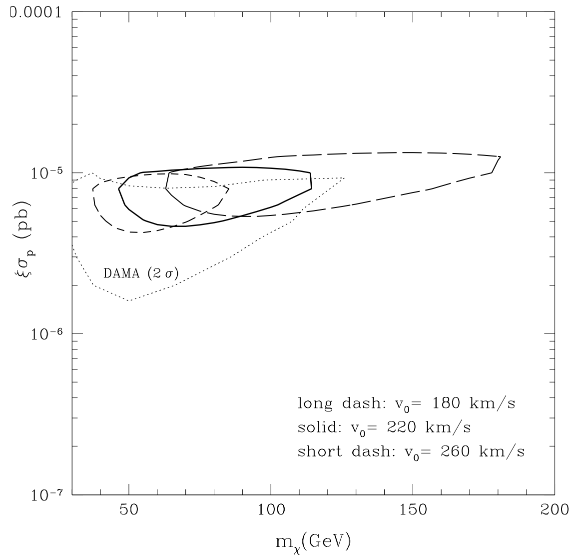

FIGURE 1. Contours of the function $\kappa = 10$ defined in the text for different values of the peak of the halo WIMP velocity distribution. Denoted by dots is the 2σ region selected by DAMA assuming $v_0 = 220\,km/s$.

Neutralinos and other SUSY particles have been constrained by searches at LEP and elsewhere. Mass limits are somewhat model dependent but are currently around 30 GeV (MSSM) to 50 GeV (CMSSM), as reviewed by J. Ellis [12]. I also refer to his talk for an explanation why higgsino-like LSPs are basically ruled out in a class of CMSSM-like models (with somewhat relaxed assumptions about unification of scalar masses).

Detection of (SUSY) WIMPs follows two broad avenues, as reviewed in separate talks [7,13]. Here I would like to make some comments about possible evidence for a WIMP signal in annual modulation. A superposition of the motion of the Earth around the Sun with that of the Sun around the center of the Milky Way leads to a small but sizeable (a few per cent) periodic variation in the effective velocity of halo WIMPs and therefore also in the detection rates [14]. The rate should reach its peak on the 2nd of June. Based on 14,962 day $\times$ kg of data, DAMA has recently reported evidence of a possible signal in their NaI(Tl) setup [15], which also confirmed DAMA's earlier indication [16] based on 4,549 day $\times$ kg of data. DAMA used a maximum likelihood method to compute in the k-th energy bin the most probable value of $S_k = S_{0,k} + S_{t,k}\cos(\omega(t-t_0))$, where $(S_{0,k})$ $S_{t,k}$ are time (in-)dependent components in the notation of Ref. [15]. The measured values of $S_{0,k}$ and $S_{t,k}$ are fitted with two parameters $\xi\sigma_p$ and $m_{\rm WIMP}$, where $\xi = \rho_{\rm WIMP}/(0.3\,{\rm GeV}/cm^3)$ and $\rho_{\rm WIMP}$ is the local density of WIMPs.

The derived ranges $m_{\rm WIMP} = 59\,{\rm GeV}^{+17}_{-14}\,{\rm GeV}$ and $\xi\sigma_p = 7.0^{+0.4}_{-1.2}\times 10^{-6}pb$ (at 99.6% CL), are in the ball-park of what one could expect from a genuine WIMP signal. We should be looking with attention for other dedicated experiments with

similar sensitivity, like CDMS or UKDMC, to soon falsify the effect. Here I would like to note that the region selected by DAMA is probably too restrictive as has been shown in Ref. [17]. (See also Ref. [20] for a crude estimate.) The effect is very sensitive to assumptions about the form of the WIMP velocity distribution in the halo. In the analysis performed by DAMA only one value of the peak of the Maxwellian velocity distribution was assumed, $v_0 = 220\,km/sec$, and only for the cored spherical isotermal model of the halo. (Several other halo models were considered in Ref. [18] and their effect on modifying direct detection rates was found to be minimal.) Since the Galactic halo has not been directly measured, quoted error bars for v_0 and the local halo density should, in my opinion, be treated only as estimates (if not "guesstimates"). Varying v_0 within a reasonable range leads to a significant enlargement of the selected region. This can be seen in Fig. 1 taken from Ref. [17] where we plot the function κ defined as

$$\kappa = \Sigma_{\text{energy bins}} \left[\left(S_{0,k} - S_{0,k}^{exp} \right)^2 / \sigma_{0,k}^2 + \left(S_{t,k} - S_{t,k}^{exp} \right)^2 / \sigma_{t,k}^2 \right], \tag{1}$$

where the $S_{.,.}$s and $S_{.,.}^{exp}$s are the calculated and measured values and the σ's are the experimental error bars given in Table 2 of Ref. [15]. We minimize κ to determine $\xi\sigma_p$ and m_{WIMP} for a given value of v_0. One can see in Fig. 1 that the region of $\kappa < 10$ which broadly matches the 2σ region of DAMA strongly depends on v_0. In particular, smaller values of v_0 allow for much larger WIMP masses to be consistent with the possible signal from DAMA [17].

Assuming that the effect reported by DAMA is caused by a genuine WIMP signal, it is interesting to ask what ranges of SUSY parameters it corresponds to. As reported here by Arnowitt [21] and Fornengo [22], it is indeed possible to find such SUSY configurations which could reproduce the signal but only for large enough $\tan\beta \gtrsim 10$. For smaller $\tan\beta$ the mass of the pseudoscalar contributing to the WIMP-nucleon cross-section becomes too small. The corresponding values of $\Omega_\chi h^2$ are typically rather small, below 0.06 (MSSM) or 0.02 (CMSSM), although larger values can also be found. I expect these conclusions to generally hold even if one neglects some arbitrariness in enlarging the experimental region of DAMA [22] (which I don't find justified [19]), and in deciding which value of *global* $\Omega_\chi h^2$ corresponds to the local WIMP density [22]. The effect of varying v_0 will have a significant impact on broadening the experimental region and therefore also on the allowed configurations of SUSY masses and couplings [19].

AXINOS

Each of the two DM candidates described above resulted from an attractive, albeit yet unconfirmed, idea in particle physics: the PQ symmetry and SUSY. Taken together, these predict an axino, the fermionic partner of the axion. Similarly to the axion, the axino couples to ordinary matter with a very tiny coupling proportional to $1/f_a$ where the allowed range of f_as was given in discussing axions.

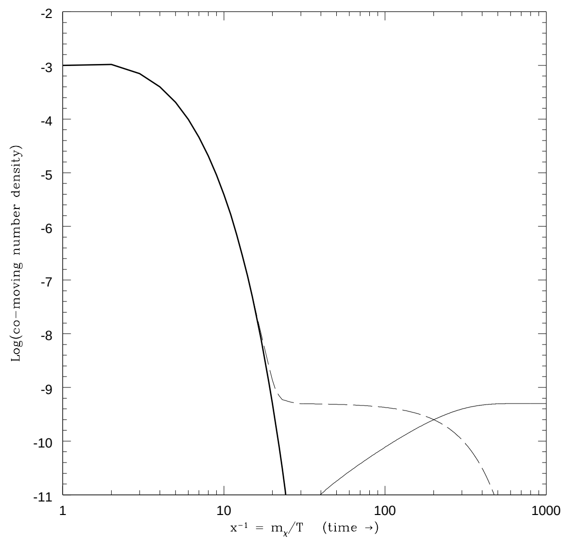

FIGURE 2. A schematic behavior of the co-moving number density: the thermal equilibrium (thick solid), NLSP neutralino (dash) and LSP axino (thin solid).

It is plausible to consider the axino as the LSP since its mass is basically a free parameter which can only be determined in specific models. As we have seen above, the neutralino has been accepted in the literature as a "canonical" candidate for the LSP and an attractive dark matter candidate. But with current LEP bounds between 30 and 50 GeV, it becomes increasingly plausible that there may well be another SUSY particle which will be lighter than the neutralino, and therefore a candidate for the LSP and dark matter.

Primordial axinos decouple from the thermal soup very early, around $T \simeq f_a$, similarly to the axions. The early study of Ragagopal, Turner and Wilczek [23] concluded that, in order to satisfy $\Omega h^2 < 1$, the primordial axino had to be light ($\lesssim 2$ keV), corresponding to warm dark matter, unless inflation would be invoked to dilute their abundance. In either case, one did not end up with axino as cold DM.

It has recently been shown [24] that the axino can be a plausible *cold* dark matter candidate after all, and that its relic density can naturally be of order the critical density. The axino can be produced as a non-thermal relic in the decays of heavier SUSY particles. Because its coupling is so much weaker, superparticles first cascade decay to the next lightest SUSY partner (NLSP) for which the most natural candidate would be the neutralino. The neutralino then freezes out from thermal equilibrium at $T_f \simeq m_\chi/20$. If it were the LSP, its co-moving number density after freeze-out would remain nearly constant. In the scenario of [24], the neutralino, after decoupling from the thermal equilibrium, subsequently decays into the axino via, *e.g.*, the process

$$\chi \to \widetilde{a}\gamma \tag{2}$$

as shown in Fig. 2. This process was already considered early on in Ref. [25] (see also [23]) in the limit of a photino NLSP and only for both the photino and axino masses assumed to be very low, $m_{\widetilde{\gamma}} \leq 1\,\mathrm{GeV}$ and $m_{\widetilde{a}} \leq 300\,\mathrm{eV}$, the former case now excluded by experiment. In that case, the photino lifetime was typically much larger than 1 second thus normally causing destruction of primordial deuterium from Big Bang nucleosynthesis (BBN) by the energetic photon of (2). Avoiding this led to lower bounds on the mass of the photino, as a function of f_a, in the MeV range [25].

Because both the NLSP neutralino and the CKR axino are both heavy (GeV mass range), the decay (2) is now typically very fast. In the theoretically most favored case of a nearly pure bino [9,11], the neutralino lifetime can be written as

$$\tau \simeq 2.12 \times 10^{-1}\mathrm{sec} \left(\frac{1}{NC_{aYY}}\right)^2 \left(\frac{f_a}{10^{11}\,\mathrm{GeV}}\right)^2 \left(\frac{50\,\mathrm{GeV}}{m_\chi}\right)^3 \tag{3}$$

where the factor NC_{aYY} is of order one. One can see that it is not difficult to ensure that the decay takes place well before 1 second in order for avoid problems with destroying successful predictions of Big Bang nucleosynthesis. The axino number density is equal to that of the NLSP neutralino. Therefore its relic abundance is

$$\Omega_{\widetilde{a}} h^2 = \left(\frac{m_{\widetilde{a}}}{m_\chi}\right) \Omega_\chi h^2. \tag{4}$$

The axinos are initially relativistic but, by the time of matter dominance they become redshifted by the expansion and become cold DM.

GRAVITINOS

Another old DM candidate has recently been re-analyzed. In the context of supergravity, there exists the fermionic partner of the graviton. Just like the graviton, it couples to ordinary matter only gravitationally with the strength $1/M_{\mathrm{P}}$ where $M_{\mathrm{P}} = 2.4 \times 10^{18}\,\mathrm{GeV}$. Gravitino's mass is model dependent but is expected to be of order the SUSY breaking scale $M_{SUSY} \lesssim 1\,\mathrm{TeV}$.

The story of primordially produced gravitinos is analogous to that of axinos. Along with gravitons, they decouple at $T \sim M_{\mathrm{P}}$. If they were the LSPs, they would "overclose the Universe", unless either $m_{\widetilde{G}} \lesssim 2\,\mathrm{keV}$ or inflation followed to dilute their density. In order for subsequent reheating not to re-populate them, one requires $T_{\mathrm{reh}} \lesssim 10^9\,\mathrm{GeV}$.

Recently, a scenario for producing thermal gravitinos in the context of leptogenesis has been considered [26]. Decays of heavy ($\sim 10^{16}\,\mathrm{GeV}$) Majorana neutrinos violate L which, via $B-L$, leads to baryon asymmetry consistent with the observed values $n_B/s \sim 10^{-9}$. For this picture to work, and assuming hierarchical neutrino

masses, the baryogenesis temperature of $T_B \sim 10^{10}\,\mathrm{GeV}$, and therefore at least as large T_{reh}, are required. Gravitinos are then produced in the thermal bath mainly via two-body processes involving gluinos. Their resulting relic abundance is given by [26]

$$\Omega_{\widetilde{G}} h^2 = 0.60 \left(\frac{T_B}{10^{10}\,\mathrm{GeV}} \right) \left(\frac{100\,\mathrm{GeV}}{m_{\widetilde{G}}} \right) \left(\frac{m_{\widetilde{g}}(\mu)}{1\,\mathrm{TeV}} \right)^2 \tag{5}$$

where $\mu \sim 100\,\mathrm{GeV}$. One can see that for plausible values of $T_B, m_{\widetilde{G}}$ and $m_{\widetilde{g}}$ one obtains $\Omega_{\widetilde{G}} h^2 \sim 1$.

One still has to make sure that the gravitinos are not produced in large numbers in out-of-equilibrium decays of the NLSP which, because of gravitino's tiny couplings, would take place long after BBN. There are ways to satisfy this, for example, when the NLSP is a higgsino in the mass range between m_W and some 300 GeV for which Ωh^2 is small enough (< 0.008). We note here that this requirement should be easily satisfied also for a bino-like NLSPs if one, or more, of the scalar leptons and squarks (except perhaps for sneutrinos and stops) is sufficiently light to suppress bino's relic abundance.

SUPER-HEAVY WIMPS: WIMPZILLAS

We have seen that plausible WIMP candidates need not couple to ordinary matter only via weak interactions, nor do they have to be produced thermally (axinos). Other possible candidates exist. For example, in a stringy scenario, these may be some class of moduli [27]. An interesting class of non-thermally produced super-heavy relics has recently been suggested [28]. (Thermally-produced WIMPs of mass above some 500 TeV would give $\Omega h^2 > 1$ [29].) Dubbed Wimpzillas, such relics could be as heavy as M_{GUT}. Moreover, they could even carry electric or color charge. One has to make sure that Wimpzillas do not annihilate efficiently enough to be in chemical equilibrium at any time. This is basically guaranteed because their number density must be very tiny in order not to "overclose" the Universe [28].

Several possible mechanisms for generating Wimpzilla-like candidates have been suggested. They could for example be produced as a result of "freezing out" quantum fluctuations at the end of inflation or by gravitational effects. First-hand description of several of them can be found in these Proceedings [28,30].

It is remarkable that the Universe, and our halo, may well be filled with such obese relics which, despite possibly large couplings to ordinary matter, would be gentle enough to remain in the (dark) background. At the end, the frightening Wimpzilla may reveal itself as a "monster with a human face".

SUMMARY

Who is the WIMP? The key to answering this question will ultimately be in the hands of experimentalists. Some attractive candidates (axion, neutralino) will hopefully be either discovered or basically ruled out during the next decade. Axinos and gravitinos, and perhaps also Wimpzillas, may well have to wait for future generations of dark matter enthusiasts.

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